UNIVERSITY OF Waterloo

Department of Mechanical and Mechatronics Engineering
ME 362 Fluid Mechanics 2

Project 1 – Flow Visualization Over an Airfoil

A Report Prepared For:
Prof. Sean D. Peterson

Prepared By:
Evan Kwon (21013390)
Makis Lam (20994505)
Ivan Lin (21021898)
Robert List (21030790)

200 University Ave W.
Waterloo, Ontario, N2L 3G1

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1.0 Project Objectives and Scope

1.1 Importance of Understanding Flow over an Airfoil

Airfoils are used in many industries that involve fluid flow such as aerospace, automotive, and energy. They play a critical role in systems that rely on fluid movement and can be used to generate lift, downforce, and thrust. Airfoils take advantage of the pressure differences generated by the flow of air or other fluids around their surfaces. As their geometry controls how the fluid moves, strategically manipulating their shape allows the tuning of forces produced by the airfoil to achieve desired outcomes.

Understanding the interaction between an airfoil and the surrounding fluid enables the development of more effective designs for aircraft wings, automotive components, turbine blades, and many other applications.

1.2 Specific Interest in Flow over an Airfoil

Fluid flow over an airfoil is of interest because it is one of the most fundamental problems studied in aerodynamics. Studying flow over an airfoil provides insight into boundary layer development, flow separation, and transition between laminar and turbulent flows. Analyzing the flow over an airfoil through visualization techniques makes it possible to observe these phenomena directly.

There is also a specific interest in studying the flow over this airfoil as it is being used in a small, fixed wing drone. The goal is to determine if there are any irregularities about this specific airfoil and if any comments about the aerodynamic performance can be made.

2.0 Experimental Setup

2.1 Strategy for Flow Visualization

The strategy to visualize the flow over the airfoil is to design and construct a scaled-down wind tunnel consisting of a fan to generate airflow, the test airfoil, and a visualization agent. To make the otherwise invisible airflow visible, smoke visualization will be integrated into the tunnel. This method has been widely adopted in experimental aerodynamics due to its effectiveness and relative simplicity. Smoke introduces tracer particles into the flow, allowing for clear observation of how air moves around the airfoil, including regions of smooth flow, separation, or turbulence.

Compared to other visualization agents such as water vapor, smoke is lightweight, minimally intrusive, and requires little prior setup. Thus, smoke visualization offers a practical and reliable means of capturing airflow behavior around the airfoil in a controlled, small-scale setup. The resulting setup is displayed in Figure 1. Incense candles will be used to produce the smoke as they are cost effective and readily available.

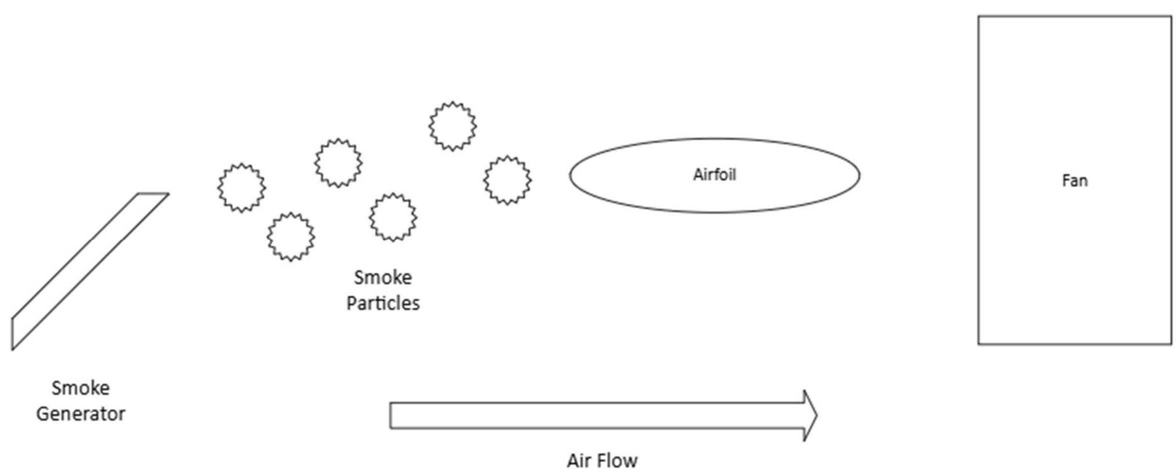

Figure 1. Experimental setup diagram

Note that the fan is located at the outlet of the wind tunnel rather than the inlet. This is done because the outlet of the fan typically produces a circular motion of air which spirals around the axis of rotation of the fan blades. For this experiment, this is undesirable and only the horizontal motion of air is wanted. For this reason, the fan inlet is positioned at the outlet of the wind tunnel acting as a puller rather than a pusher to avoid spiral turbulence. A camera on a tripod will be set to record video to ensure that each frame is captured and after the experiment is completed, the frames will be selected based on the quality of the flow visualization.

Figure 2 illustrates the physical setup. It should be noted that there is no container for the wind tunnel but instead it is left to open air. This was done because originally the cardboard container for the walls of the wind tunnel provided poor contrast to capture the smoke. Having it in open air did not provide too much trouble and yielded good results.

Figure 2. Physical experimental setup

3.0 Background Information

At the surface of an object interacting with the flow of a fluid, there is typically no tangential velocity or no slip at that boundary as shown in Figure 3. This is called the no slip condition.

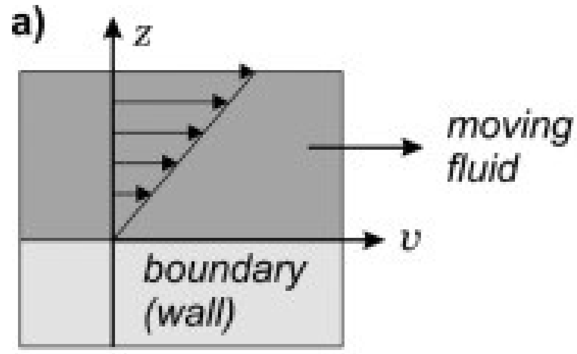

Figure 3. No slip condition [1]

The no slip condition is an assumption made because the fluid molecules repeatedly collide and exchange energy with the surface. These collisions combined with viscous friction and intermolecular adhesion forces (van der Waals, electrostatic) lead to very little velocity right at the surface of the object. This assumption also has strong experimental support with small slip only emerging at nano or microscales, special surfaces, or complex fluids [1].

Due to this no slip condition, a velocity gradient develops in a similar fashion to that shown in Figure 3. This velocity leads to a thin region near the surface of the solid body where viscous effects dominate and the velocity of the fluid changes rapidly from the wall value to the free-stream value or in other words, the boundary layer is the region of space where the fluid velocity goes from zero to the free flow speed. This is very important as a boundary layer means that the airflow over the solid body follows the curvature and geometry of the airfoil. Different shapes can be used to manipulate the flow direction and the speed of the flow. This leads to a discussion about the importance of Bernoulli's Principle as displayed in Equation 1.

$$\mathrm{P} + \frac{\rho V^2}{2} + \rho g h = \text{Constant} \quad (1)$$

This equation governs how pressure and velocity of a fluid are proportional to one another along a streamline. Most importantly, it shows that if the fluid velocity increases, that means that the pressure will decrease by a proportional amount. This is the general mechanism for lift generation.

The lower pressure on the top surface of an airfoil due to the higher velocity created by the geometric manipulation of the flow, allowed by the boundary layer, creates an upward force due to the pressure imbalance and thus a lifting force. This shows the importance of the boundary layer since in the case that the flow separates, it is no longer being manipulated by the curvature of the airfoil and thus there is no pressure differential and therefore no lift [2].

Generally, the boundary layer of an airfoil can be described in two regions. The laminar region, where the airflow sticks to the surface of the wing, and the turbulent region, where the airflow no longer sticks to the surface of the airfoil. These two regions are separated by the "separation point." A simplified way of looking at the section generating lift is by looking at the laminar region. If the entire boundary layer is laminar, that means that the whole section along the chord is generating lift. This boundary layer is visualized in Figure 4.

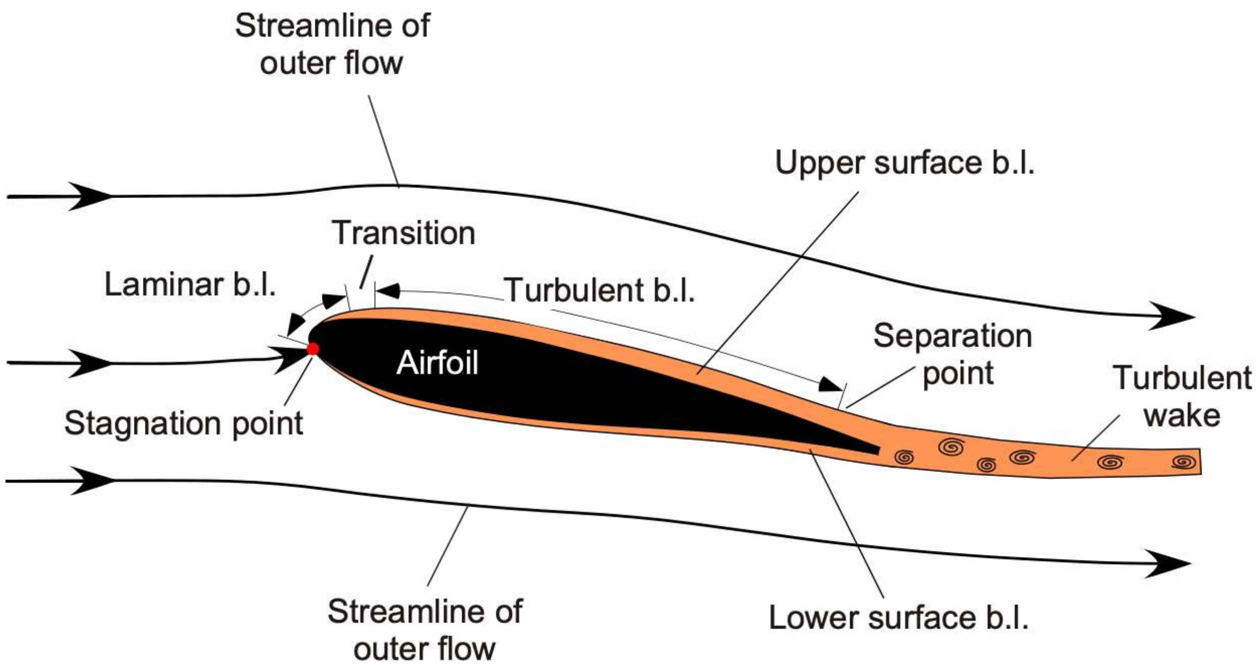

Figure 4. Boundary layer over an airfoil [3]

4.0 Observational Analysis

4.1 Boundary Layer Visualization

Examining the images gathered from the experiment, observations can be made about the airfoil and how air flows past it. Firstly, there appears to be a layer of smoke that sits on the surface of the airfoil as seen in Figure 5. This smoke sticks to the airfoil almost to the end of the chord line even when the smoke is moving along the longitudinal direction.

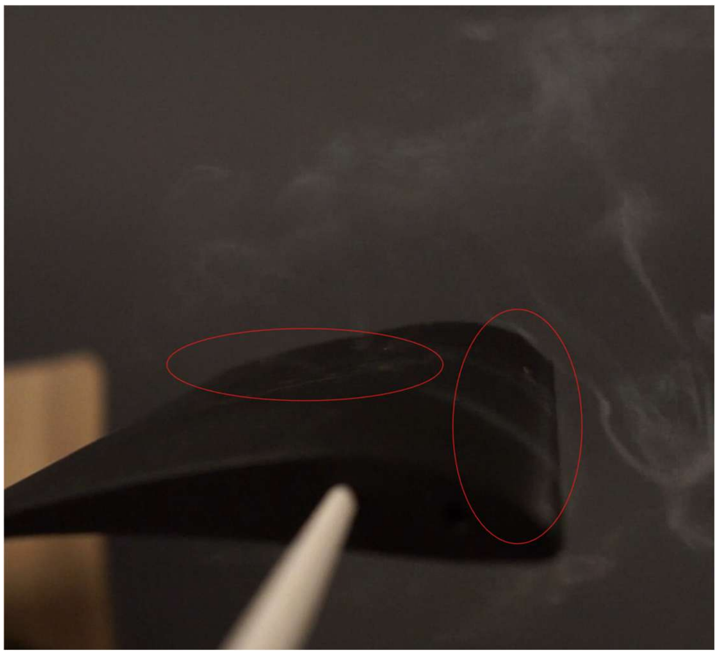

Figure 5. Boundary layer visualization

This observation is important in validating the function of the airfoil. Since the function of the airfoil is to generate lift, it shows that the no-slip condition is held true and that there is indeed a boundary layer of air that is sticking to the wing. With the understanding of the background information presented in the previous section, this means that the airfoil is generating lift. A separation point would look like a rapid detachment of the smoke away from the surface of the airfoil meaning that the air is no longer following the curvature of the wing but instead is turbulent and following the influences of other things.

The location of the separation point can be expected to be relatively aft along the chord as there is no angle of attack for the airfoil. This means that the flow over the whole airfoil is likely laminar and is generating lift [4].

4.2 Transition from Laminar to Turbulent Flow

Observing the smoke trails over the airfoil for a different trial of the experiment, a clear separation from laminar to turbulent flow can be seen. For moments where the initial smoke trail is laminar, the flow stays laminar over the first part of the airfoil and then separates off the airfoil and becomes turbulent. Figure 6 shows this phenomenon, with an initial laminar flow coming from the incense, a laminar flow over the airfoil, and a turbulent separation above and behind the airfoil.

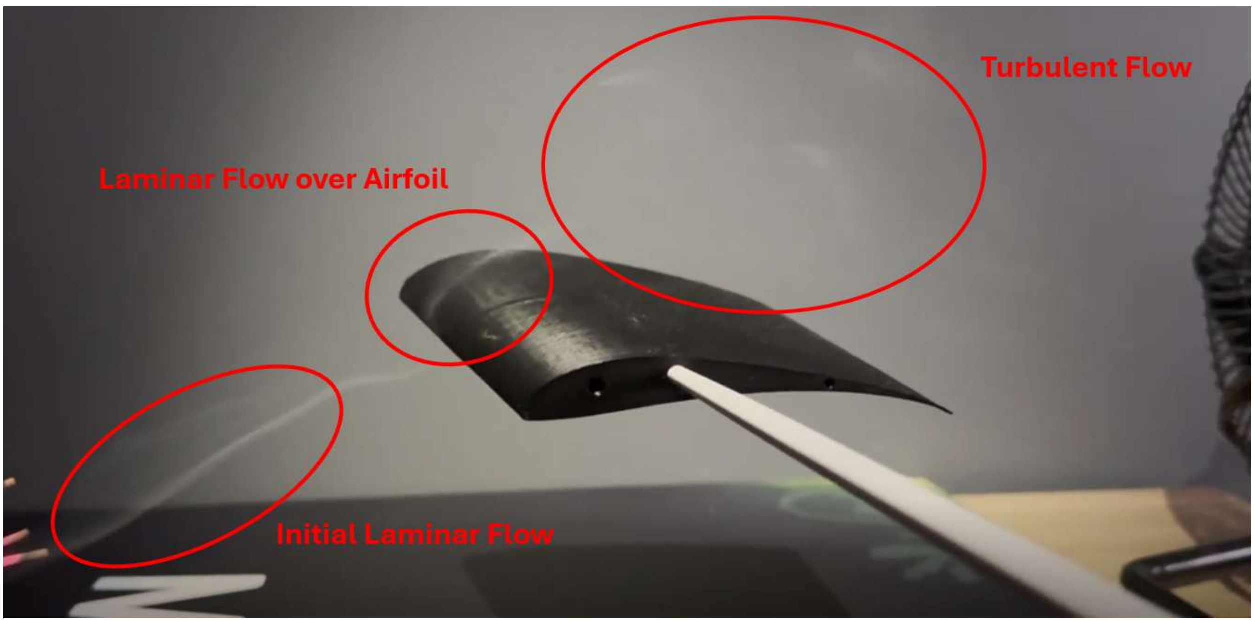

Figure 6. Transition from laminar to turbulent flow over airfoil

This behavior aligns with what is expected for an airfoil and implies that the airfoil is working and producing lift. However, the turbulent flow starts almost directly after the leading edge of the airfoil, and there is no visible laminar flow near the trailing edge of the airfoil. This could mean that the flow is not sticking on the airfoil for the full chord length, or there could be other factors at play causing the smoke particles to follow a different trajectory. As this airfoil is at a 0-degree angle of attack, this separation of flow should not occur, and this should be investigated further with a higher fidelity flow visualization to understand why this occurred.

4.3 Effect of Angle of Attack

When the airfoil is positioned neutrally (tilted neither up nor down), the incense smoke is laminar as it flows past the stagnation point and separates above and below the airfoil, with turbulent flow arising after the smoke has passed the transition point near the "apex" of the airfoil (the top hump of the airfoil). This can be seen in Figure 7 below.

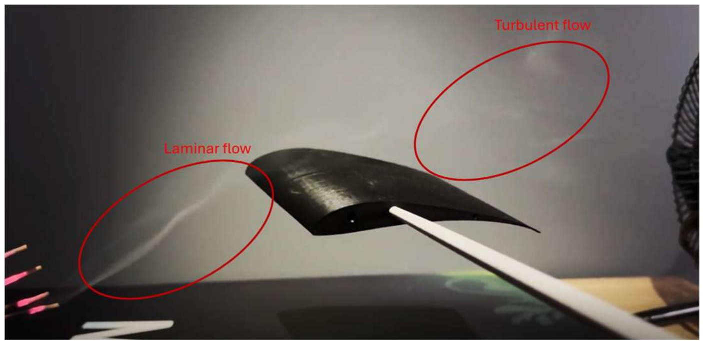

Figure 7. Transition from laminar to turbulent flow for airfoil with neutral angle of attack

However, when pitching the airfoil up (changing the angle of attack), it was observed that the flow of smoke broke off from the top surface of the airfoil and became turbulent much sooner. When pitching the airfoil downwards, the same effect was observed, with the flow of smoke breaking off immediately from the airfoil and transitioning into turbulent flow. The flow effects from pitching the airfoil up and down can be observed below in Figure 8 and Figure 9.

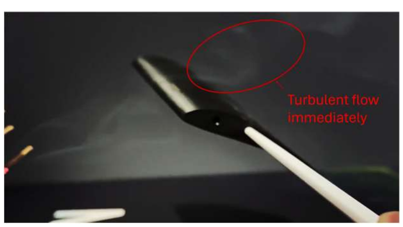

Figure 8. Rapid transition to turbulent flow on airfoil with positive angle of attack

Figure 9. Rapid transition to turbulent flow on airfoil with negative angle of attack

The lift and drag coefficients of an airfoil are both functions of the angle of attack. The drag coefficient increases with continuous change in one direction of the angle of attack, be it positive or negative. The lift coefficient increases with an increase in the angle of attack, until a certain point at which it drops off sharply; this is known as stall [5]. During stall, the boundary layer struggles to stay attached, and the airfoil begins to exhibit separated and turbulent flow, as seen in Figure 8 and Figure 9.

4.4 Vortex Formation

Looking at when the airfoil is positioned at a negative angle of attack, the smoke streaklines begin to split from the upper surface. Figure 10 shows a sequence of frames where initially smooth streaklines near the leading edge begin to distort and roll into spiral-like patterns underneath the airfoil toward the trailing edge. These formations indicate the development of vortices and are a strong indication of turbulence since the flow is chaotic with disorderly movement. As the smoke continues downstream, it loses rotational motion and gradually disperses into the surrounding air. This behavior represents a loss of rotational kinetic energy caused by viscous shearing and mixing with the surrounding fluid [6].

(a) Initial flow *(b) Vortex formation 1* *(c) Vortex formation 2*

Figure 10. Formation of vortices at a negative angle of attack

At a higher negative angle of attack, this phenomenon becomes more evident. As shown in Figure 11, multiple adjacent vortices can be observed forming along the path of flow, creating wave-like patterns. The vortices are closely packed, causing them to interact with each other and stretch. It can be inferred that turbulence increases because of stronger vortex interaction.

Figure 11. Wave-like pattern at an aggressive negative angle of attack

At such high negative angle of attack, the surface at the leading edge curves sharply, and the smoke separates from the lower surface of the airfoil. These disturbances behind the airfoil, such as vortices, are known as wake turbulence. In real world applications, this phenomenon is important to consider, as it directly affects drag, stability, and efficiency of airfoils. For example, in aviation wake turbulence can cause instability or loss of control in aircrafts [7].

4.5 Conclusions

As per the specific interest of the group, the goal was to understand how this specific airfoil interacts with the air and if there are any irregularities which would lead to this airfoil not being a good candidate to be used in a fixed wing drone. The most notable and applicable observation is the stark separation between the boundary layer and the wing at a relatively forward position along the chord. One image shows the boundary layer continuing to the end of the chord and the other shows separation. There can be multiple factors for why this occurs, but a more detailed and higher fidelity flow visualization and analysis are required to validate the aerodynamics of this airfoil.

Otherwise, all other observed behaviors of this flow are typical and expected such as the relation between angle of attack and location of transition point from laminar to turbulent. As angle of attack increases in either positive or negative directions, there is more flow that is separated thus not generating lift. This observation is important, and further work can be done to quantify a critical angle of attack which will dictate the maximum angle of attack that can be achieved before a stall occurs.

5.0 Experimental Limitations

As seen from the images, this experiment brings a good initial understanding of the behavior of air over an airfoil; however, this setup is very limited. Firstly, the smoke generation agent or in this case the incense candles were not producing smoke at a constant rate. This means that some of the effects seen in the air flow can be attributed to variations in how the incense candles were burning rather than purely a reflection of how the air was behaving.

In addition, as a biproduct of using a candle to produce smoke, there is heat that is affecting the smoke particles. Heat generally causes air to rise as it decreases the density of the air and excites the molecules to spread out more. This affects the movement of the air as the smoke tends to rise. This likely affected the boundary layer and the separation point of the smoke as there is an inherent force acting on the air to cause it to rise upward instead of sticking to the surface.

Lastly, the experiment did not use an enclosure to isolate the system and so the airflow was prone to disturbances like open windows or other events happening nearby. In an ideal scenario, all these other factors would be controlled so that only one variable such as angle of attack is changed and can be studied. Temperature, pressure, humidity, and various other factors should be fixed to allow for the best experimental results.

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